

The Role of Epimysium in Suturing Skeletal Muscle Lacerations

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- BACKGROUND:** Direct muscle trauma is a common and disabling clinical problem. Surgical muscle repair is difficult to evaluate because reliable repair techniques have not been established scientifically. The purpose of this study was to assess the biomechanical properties of epimysium, the collagenous tissue sheath that surrounds muscles in the body.
- STUDY DESIGN:** We surgically repaired transected porcine muscle bellies with and without epimysium. For both groups, 25 figure-eight stitches in lacerated quadriceps bellies from a euthanatized pig were loaded under tension on a biomechanical machine (model 8521S, Instron Company). Maximum loads and strains were measured and mechanisms of failure recorded.
- RESULTS:** The mean load for repairs with epimysium (25.1 N) was significantly higher ($p = 0.034$) than that for repairs without epimysium (21.2 N). The mean strain for repairs with epimysium (10.4%) was significantly higher ($p < 0.001$) than that for repairs without epimysium (7.3%). The mechanisms of failure were also different. Among epimysium repairs, 15 stitches avulsed muscle transversely, and 10 stitches tore out longitudinally from the muscle. In the nonepimysium group, 1 suture avulsed muscle and 24 sutures tore out. Muscle was the weakest element in each test.
- CONCLUSIONS:** These data showed that epimysium incorporation into suturing improves the capacity of repairs to bear force. These findings fill a knowledge gap and may improve outcomes of muscle suturing. By focusing the experiment on biomechanical properties of muscle stitching, this study showed the key role epimysium plays in muscle suturing. (J Am Coll Surg 2005;200:38–44. © 2005 by the American College of Surgeons)
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Direct muscle trauma is common in medicine.^{1,2} For the most part, muscle trauma is treated without surgery and with rest, ice, compression, and elevation, because repair of muscle lacerations without tendon involvement is technically demanding and the likelihood of clinical failure is high.^{3–5} Recent animal and human data have challenged the indications for nonoperative care, particu-

larly in cases of muscle transections.^{6–11} Clinical results of muscle laceration repair hinge on how well sutured muscle repair constructs bear loading. Immediate repair strength is important because healing is better when motion is started 5 days after repair.¹² Longer immobilization leads to inferior healing, atrophy, scarring, longer recovery times, and increased risk of rerupture.¹² A better understanding of the mechanisms of failure is key to development of optimal repair techniques. Improving muscle laceration treatment is a clinical and laboratory research topic for us, and this study represents the first of a proposed experimental series to investigate strategies in successfully treating severe muscle disruptions.⁹

The role of epimysium, the connective tissue sheath around a muscle, is not well defined in surgical repair. Epimysium-based repair has been reported to be important for superior stitching of forearm muscle belly lacerations.⁶ A review of the literature found no study comparing suturing data for muscle with and without epimysium. Because epimysium is the thickest connec-

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tive tissue in muscle bellies,^{13 14} it was hypothesized that repair of muscle bellies with epimysium could elucidate the role of epimysium-based muscle repair when compared with repair without epimysium.

A biomechanical study was designed to test sutures in animal muscle belly transections focusing on the passive characteristics of sutured constructs. The purpose of this study was to compare forces, strains, and mechanisms of failure of sutured muscle bellies with and without epimysium.

METHODS

Materials and animals

An immature female Yorkshire cross pig weighing approximately 40 kg was acquired from a local Class-A vendor (HDH Farms). The animal was maintained in an Association for Assessment and Accreditation of Laboratory Animal Care International accredited facility and cared for in strict accordance with the 1996 *Guide for the Care and Use of Laboratory Animals* by the National Research Council. The pig was euthanatized in the course of another study. A cadaver limb was obtained from a protocol approved by the Animal Care and Use Committee of the US Army Institute of Surgical Research, and this study (protocol C2002.092e) was approved by the institutional review board.

Preparation

The limb was refrigerated at 4°C for 44 hours. The quadriceps femoris muscles were dissected, and these four muscles were used for this study. Compartmental fascia was removed with care to preserve epimysium. Muscle belly lacerations were made in areas where no tendon was present, and saline was used to moisten specimens during testing. For specimens in the epimysium group, sutures were placed about the edge of the laceration, as is done in clinical practice for epimyseal-based surgical repair, with figure-eight stitches of metric size 5 braided polyester suture. One suture was used for each test, and different belly areas of the quadriceps muscle were used for the experiment. A stitch was placed at the tendon end of the muscle using a running interlocking technique, and then the specimen was loaded on a biomechanical testing machine. To test sutures without epimysium, muscle areas had epimysium removed surgically and were otherwise stitched and prepared in the same fashion as the epimysium group.

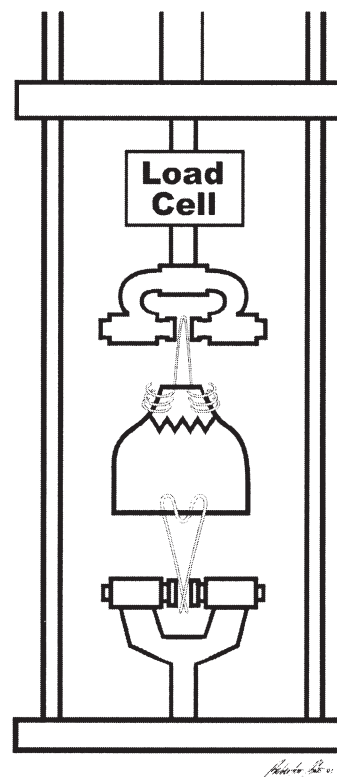


Figure 1. Materials testing system. The figure-eight suture is gripped below, and the tendon suture is gripped above. The muscle specimen is a half belly transected in the middle.

Study design

A biomechanical testing protocol was designed for measuring the performance of sutures in muscle belly lacerations. Two groups were tested: muscle specimens with and without epimysium. Parameters compared were maximum load, strain at maximum load, and mechanism of failure. In this way, each stitch test yielded a maximum load, a strain, and a mechanism of failure.

Biomechanical testing

The Instron 8521S materials testing machine (Instron Corporation) was used in a uniaxial set up (Fig. 1). Under position control using a 0.1 kN load cell, the servohydraulic tester applied tension in the long, anatomic axis of the muscle organ, and the stitch and tendon sutures were held in standard grips with leather facing. The modeling tested the passive properties of the specimen in approximation of the clinical situation.⁹ The construct was preloaded minimally with 5 to 8 N to remove slack immediately before testing. Stitched muscles were loaded longitudinally at an elongation rate of 25 mm per minute until failure. Strain at failure was

Table 1. Biomechanical Data Summary of Stitch Performance in Muscle Bellies

Variables	Epimysium (mean \pm SD)	No epimysium (mean \pm SD)	p Value
Maximum load (Newtons)	25.1 \pm 5.8	21.2 \pm 6.8	0.034
Strain (mm/mm \times 100%)	10.4 \pm 2.4	7.3 \pm 2.6	<0.001

Surgical repairs incorporated epimysium (Epimysium column) or did not (No epimysium column). Both load and strain means were significantly different.

calculated from the total displacement of the actuator. Two modes of failure were defined: suture tear out, when sutures pulled out longitudinally from the muscle, and avulsion, when muscle failed transversely and a piece of muscle was removed as the suture loop squeezed and closed during tensioning.

Data analysis

Series IX software (Instron Corporation) was used for data collection, and the system recorded load and strain data simultaneously with testing as biomechanical parameters of stitch performance. Units for maximum load were newtons, and the strain at maximum load was in millimeters per millimeters expressed as a percent. The mechanism of failure was observed directly and recorded.

Independent sample *t*-tests were used as the test statistic for loads and strains, and Levene's test was used for assessing equality of variances. For mechanism of failure analysis, a 2×2 contingency test was used with Fisher's exact test because of the small sample sizes. A *p* value less than 0.05 was considered significant. Data was entered into a Microsoft Excel spreadsheet (Microsoft Inc), and SPSS version 11.5 (SPSS Inc) was used for statistical analysis.

RESULTS

For loads, the difference between group means was significant ($p = 0.034$). The load results are summarized in Table 1 and Figure 2. The mean maximum load for repairs with epimysium was 25.1 N; that for repairs without epimysium was 21.2 N.

For strains, the difference between group means was also significant ($p < 0.001$), and results are displayed in Table 1 and Figure 3. The mean strain at maximum load for repairs with epimysium was 10.4%; that for repairs without epimysium was 7.3%.

There was a distinct difference in the mechanisms of

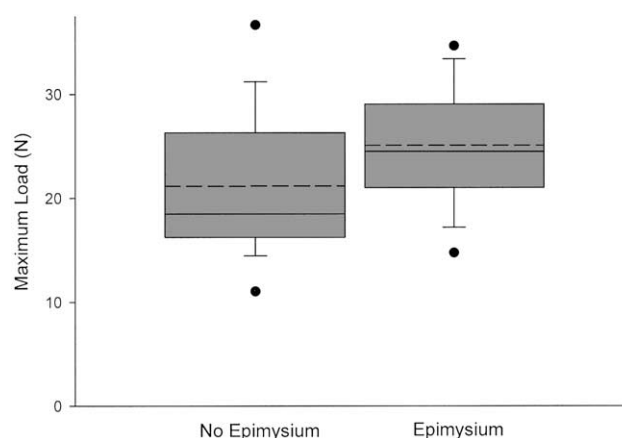


Figure 2. Maximum load data of sutured muscle bellies with and without epimysium. The error bars express a range of one standard deviation above and below the mean. Loads are expressed in newtons (N). The gray box plots have the 25th and 75th % confidence limits as the lower and upper borders, respectively. The dots are the 95% confidence limits. The mean is a dashed line within the gray box and the median is a solid line within the gray box. The mean maximum loads differed significantly between groups ($p = 0.034$).

failure between groups ($p < 0.0001$). One repair stitch with epimysium avulsed muscle, and 24 sutures failed by tear out of the muscle. Fifteen repair stitches without epimysium avulsed muscle, and 10 sutures tore out (Table 2). The weakest element was the sutured portion of the muscle in each specimen and test. No slippage

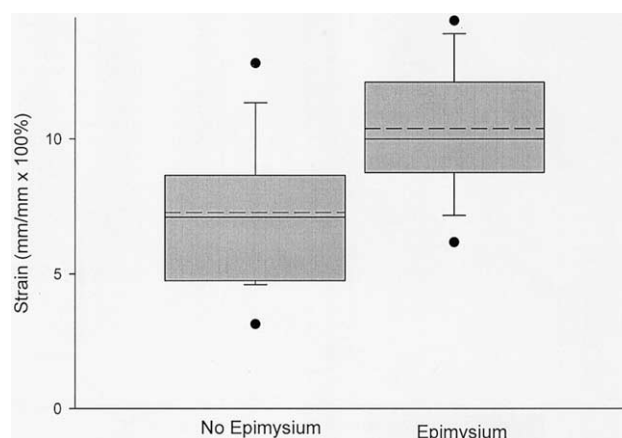


Figure 3. Strain data of stitches in muscle with and without epimysium. The error bars express a range of one standard deviation from the mean. Strain is expressed in millimeters per millimeters as a percent. The gray box plots have the 25th and 75th % confidence limits as the lower and upper borders respectively. The dots are the 95% confidence limits. The mean is a dashed line within the gray box and the median is a solid line within the gray box. The difference between groups in mean strains at maximum load is significant ($p < 0.001$).

Table 2. Summary of Mechanism of Failure Data of Sutures Pulled from Muscles

Variables	Epimysium	No epimysium	p Value
Number of stitches	25	25	
Mechanisms of failure (tear outs/transections)	10/15	24/1	<0.0001
Tear out proportion (tear outs/total) \times 100%	40	96	

The mechanisms of failure were different between groups; the Epimysium group had 15 times more transections than the No epimysium group.

occurred, and all deformations observed occurred only in the sutured portion of the muscle.

DISCUSSION

This study demonstrated the mechanisms of failure and success of stitches in lacerated muscle bellies by improving understanding of how sutured muscle fails or successfully bears load. The model mimicked closely the clinical situation and validated the method by showing the weakest link to be the muscle. The difference in mean loads is clinically notable because a difference of 3.9N per stitch can sum to high loads when, for example, about 20 stitches make up a muscle repair for a biceps brachii transection. Because 10N is a low and 17N is a high force threshold in rehabilitation protocols of hand flexor tendon repair, values from the current study are of direct clinical relevance.

The clinical strength of stitches in sutured muscle was clearly better with epimysium by all parameters measured: loads, strains, and failure modes. The role of epimysium was important, and the known architecture of epimysium should offer surgeons a tissue with capacity to bear tensile loads passively (Fig. 4). The epimysium, the outer connective tissue sheath of muscle, is thicker and denser collagen than the endomysium. Epimysium is made of densely packed collagen bundles that are organized by elastin fibers (arrows). These structural differences underlie the biomechanical reasons why epimysium was loaded more, strained more, and failed differently than muscle sutured without epimysium. Suturing techniques that use a transverse throw, or suture limb that loads the collagen fibers transversely can load the connective tissue of muscle more than the figure-eight technique studied here, and the difference between epimysial-based repair and repair without epimysium may be even greater with more advanced suturing techniques now in use.⁹ Much information about repair of musculotendinous structures comes from research and

care for repair of flexor tendon injuries of the hand, and much of what we do not know about surgical repair of muscle can initially be researched in testing of lessons learned from tendon repair. Epitendinous repair has become a common practice because of its biomechanical strength, and we found a similar advantage in epimysial-based repair in muscle bellies.

This investigation demonstrated that incorporation of the epimysium improves surgical repair because incorporation of fibrous portions of the muscle improves tension bearing. In muscle belly lacerations, the passive property knowledge gap is unfortunate because the surgeon is faced with a technically challenging repair of delicate tissues. The surgeon with knowledge of the specific capacities of muscle tissues to hold sutures can optimize structural repair. The passive properties of the tissues are key because they provide the capacity to hold stitches. The epimysium-deep fascia interface can become obliterated when the epimysium is disrupted,¹⁵ and the clinical scarring between the epimysium and fascia we have seen in operations can limit muscle sliding under the fascia.^{8,9} Restoration of the epimysium by repair may permit better sliding, and fascia turndown, reported by Heckman and Levine,⁸ may also disturb the sliding properties. The stitched muscle must bear passive and active forces for clinical success with proper sliding and contraction to include overcoming epimysium-to-fascia scarring. After muscle laceration, healing results in scar tissue in the gap between the transected portions of the muscle. A large scar, in turn, results in a considerable loss of muscle function, with a propensity for reinjury.⁵ But with proper surgical intervention, the extent of gapping and scarring can be reduced as muscle is reunited, resulting in improved outcomes.

The findings of this study apply to numerous and diverse stakeholders including health care providers, investigators, educators, and patients.¹⁶⁻²⁶ Traumatic injuries can affect muscles within the clinical scope of all surgical specialties, and iatrogenic muscle laceration or transection can require repair.²² Muscle suturing has impact on surgical approaches, exploration and debridement, myotomy, laceration repair, rupture or transection suturing, muscle transfer or flaps and coverage procedures, muscle grafting or transplantation, limb replantation or reconstruction, and even amputations and myoplasty.^{8,9,22-25} Muscle disruption is important to sports medicine providers, therapists, and athletic trainers.^{2,7,12} Researchers, investigators, anatomists, bioengineers, and exercise physiologists actively study pro-

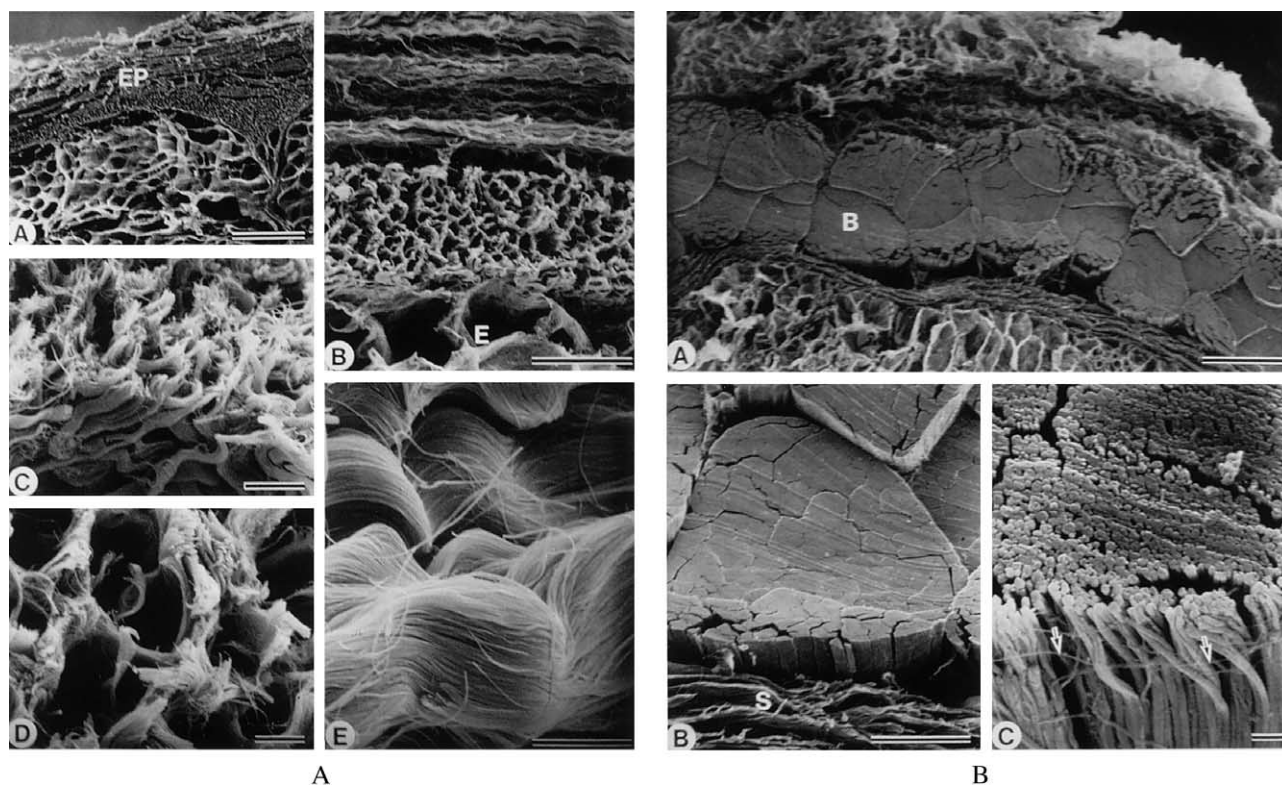


Figure 4. (A) Electron micrographs of muscular connective tissue. A) Epimysium (EP) has outer and inner layers ($\times 70$, Bar = 300 μm). B) The inner layer of epimysium has many collagen fibers in a wavy pattern in contact with the endomysium (E) ($\times 550$, Bar = 50 μm). C) Close up of collagen fibers of inner layer of epimysium. The fibers run longitudinal to the long axis of the muscle fiber ($\times 1,600$, Bar = 10 μm). D) Magnification of C displaying pattern of collagen fibers ($\times 2,700$, Bar = 5 μm). E) Outer layer of epimysium with wavy sheets of collagen fibers ($\times 5,500$, Bar = 5 μm). Bovine semitendinosus specimens were prepared with a cell maceration technique. (From: Nishimura T, Hattori A, Takahashi K. Ultrastructure of the intramuscular connective tissue in bovine skeletal muscle. A demonstration using the cell-maceration/scanning electron microscope method. *Acta Anatomica* 1994;151:250–257, with permission). B) Electron micrographs of muscular connective tissue. A) Epimysium with collagen bundles (B) ($\times 80$, Bar = 500 μm). B) Higher magnification of A displaying bundles surrounded by collagen sheets (S) ($\times 300$, Bar = 100 μm). C) Close up of B showing collagen bundles of thousands of fibrils with fine fibrils (arrowheads) running around bundles ($\times 11,000$, Bar = 1 μm). Bovine semitendinosus specimens were prepared with a cell maceration technique. (From: Nishimura T, Hattori A, Takahashi K. Ultrastructure of the intramuscular connective tissue in bovine skeletal muscle. A demonstration using the cell-maceration/scanning electron microscope method. *Acta Anatomica* 1994;151:250–257, with permission).

cesses related to the findings of this study. The findings can stimulate researchers to focus more on a little studied but important topic.^{5,14 16 26–29} Educators in anatomy and physiology can note the importance of the epimysium in textbooks and classes that may help increase awareness of the importance of the epimysium in injured patients.^{26,30,31}

Additional results of our study regarded the supporting strain data and mechanisms of failure. The two supporting findings added to the main load findings in regard to improved stitch performance. Similar to the load findings, the strain data showed worse stitch performance when no epimysium was in the repair. The mechanisms of failure differ because the way the tissues are loaded are different with and without epimysium in the repair. If the sutures without epimysium could have held

longer in the muscle, then the deformation and strain of the muscle would have been more like the epimysium-based repair. Because the stitch without epimysium gained less hold or purchase without the extra connective tissue provided by the epimysium, the repair without epimysium produced less deformation and strain and failed by tear out. Epimysium incorporation permitted greater deformation and strain and failure by muscle transverse transection; the stitch held more tissue better. Connective tissue fibers in the muscle belly consist mainly of collagen, and the dominant direction for fibers is longitudinal (Fig. 4).¹³ Some data about connective tissue fibers during elongation showed that the collagen fibers become more longitudinally oriented on stretching, recover orientation during relaxation, and the elastic

fibers aid the collagen in recovering resting orientation.²⁸ Longitudinal fiber orientation could explain why transverse stitching may hold better than longitudinal stitching. Sutures crossing collagen fibers appear to load the fibers more successfully than longitudinal stitches that lose hold lengthwise between collagen fibers before tearing out. Other noncollagenous matrix proteins in muscle bellies such as fibronectin, thrombospondin-1, vitronectin, and undulin have been identified^{30,31} and may have roles in stitch performance. The strain and mechanism of failure findings of this study complemented the load findings.

The new knowledge introduced by this study entailed a novel application of biomechanical testing in investigating the passive properties of muscle stitching. Many studies of passive properties of muscles are in a strain context^{4,32-34} without a specific surgical context, as outlined here. The combination of an established method, ie, biomechanical testing, with a different topic, ie, muscle belly suturing, yielded new data that improved understanding of stitch performance. We are not aware of any other study that looks at material testing of muscle repair. Linking of biomechanical data here and previous biochemical and histologic knowledge^{13,14} (Fig. 4) elucidated an incompletely understood clinical problem. The role of epimysium in stitching is central to this and an increase in the surgical strength of early repairs may improve chances of clinical success.

The strengths of this study are the experimental design in consideration of a difficult clinical problem, and the application of biomechanical testing to muscle belly lacerations. There have been clinical reports about muscle belly repair^{6,8,35} and animal studies advocating repair,^{7,10} but there are few experiments focused on muscle belly stitching. By addressing the role of epimysium in suturing, this study helps clinicians, researchers, and educators in understanding what epimysium is and why it is important. By linking disparate scientific contexts such as biomechanical testing and muscle microstructure, this study brings together information to enable a coherent understanding of the role of epimysium in muscle stitch performance. By experimentation, this study helps in developing optimal repair techniques by improving understanding of how sutured muscle fails and bears load.

The weakness of this study regards the limited scope of the experiment because we were concerned about determining the role of epimysium in muscle belly stitching.

The findings may not be applicable beyond that focus. We did not focus on issues related to regional variability of the epimysium,¹⁴ myofiber types, or superficial or deep muscles, although these could affect the connective tissue content of muscle bellies. The model needs additional development to test fresh muscles in more and varied conditions. Direct tendon gripping would have made the construct with one less link, but would have taken more time to test, and no slippage occurred. Subfailure properties, gap formation, cyclic loading, whole muscle repairs, and healing effects after repair are areas for additional study.

In summary, this study established that incorporation of the epimysium into muscle repair considerably improves the biomechanical properties of sutured muscle bellies as compared with repairs without epimysium.

Author Contributions

Study conception and design: Kragh, Svoboda

Acquisition of data: Kragh, Brooks, Bice

Drafting of manuscript: Kragh, Svoboda, Wenke, Walters

Critical revision: Svoboda, Wenke, Brooks, Bice, Walters

Statistical expertise: Kragh, Wenke

Obtaining funding: Kragh

Supervision: Kragh, Walters

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